Plasmon-based losses in OLEDs

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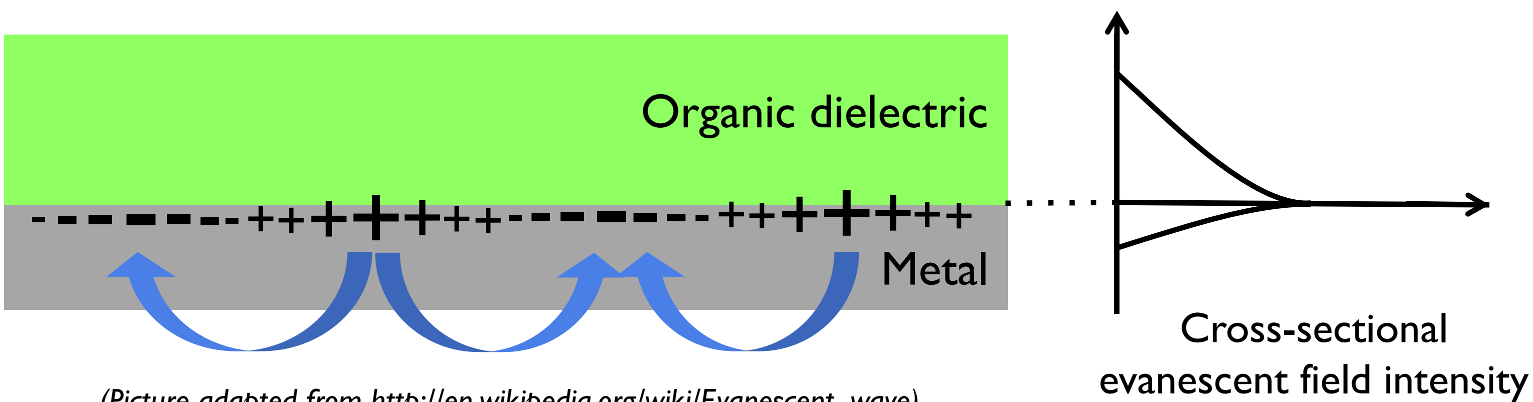
Surface-Plasmon Polariton Waves

<u>What are SPP waves?</u>

Charge density oscillations associated with evanescent waves, propagating along a dielectric (organic layer) – metal (electrode) interface



(Picture adapted from http://en.wikipedia.org/wiki/Evanescent_wave)

Highly effective coupling from light emitted from radiating dipoles in OLEDs to SPP waves leads to significant energy loss (in certain cases, up to 80%).

What affects the SPP loss in OLEDs?

1. **Distance between emitting dipole and metal electrode**

   Since coupling to SPP modes is a ***near-field effect***,
   it can be reduced by increasing distance between emitter and metal electrode.
   - *p*- or *n*- doping of transport layer required to maintain low turn-on voltage
   - In this way, SPP loss reduction traded off for increased waveguide losses

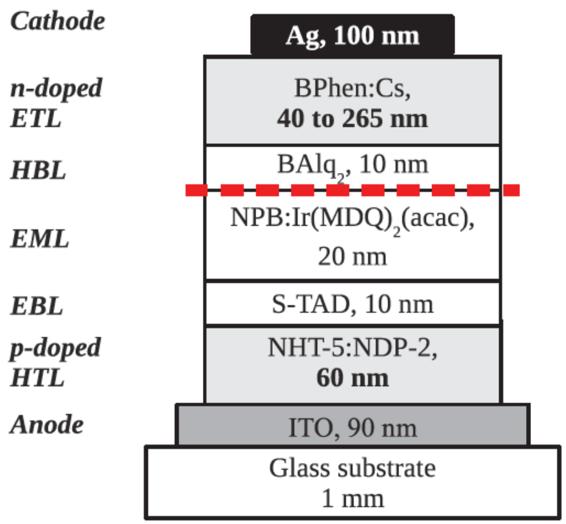
2. Dipole orientation direction

   Horizontally oriented dipole can greatly reduce the SPP loss modes and *directly increase outcoupling efficiency* [*JAP*, **88**, 1073 (2000)]
   - Material choice or structural templating required to control orientation

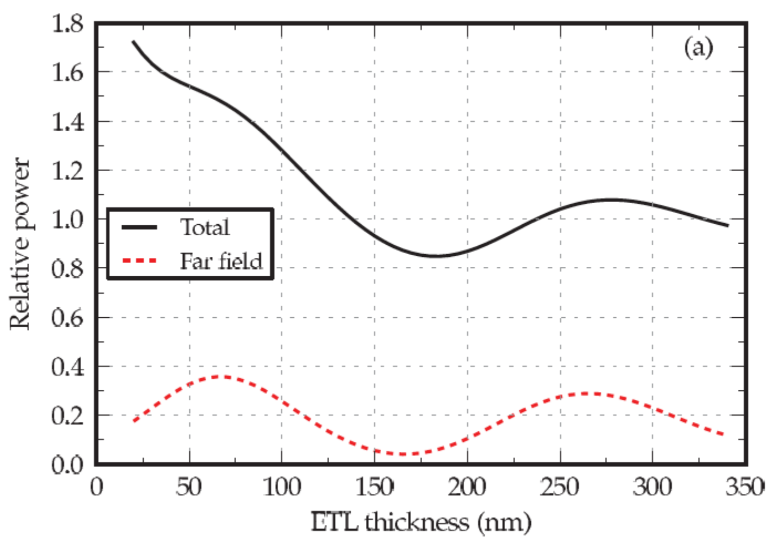
3. **Structured metal contact**

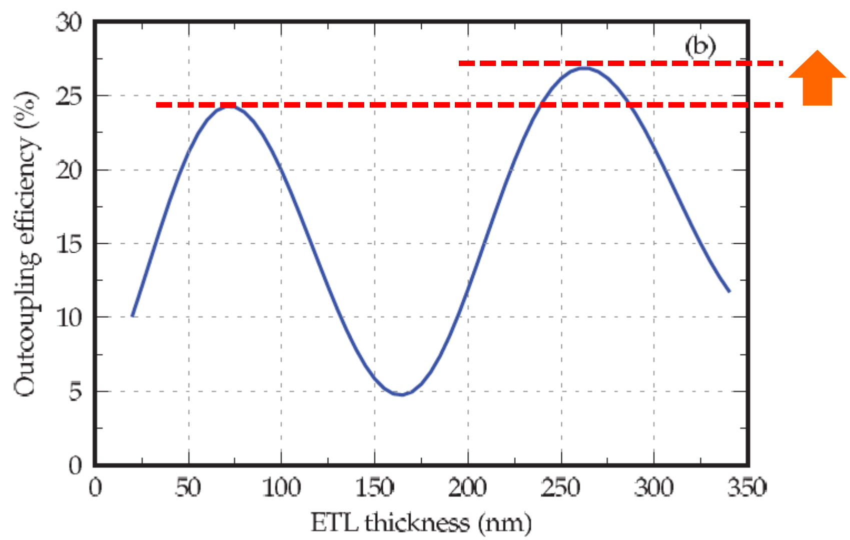
   Random structures introduced into OLEDs lead to corrugated metal layer, instead of typical planar metal layer with heavy SPP loss.
   By introducing randomness in surface structures, SPP modes could be Bragg-scattered into visible light with reduced wavelength/angle dependence.

SPP mode recovery – thicker transport layer



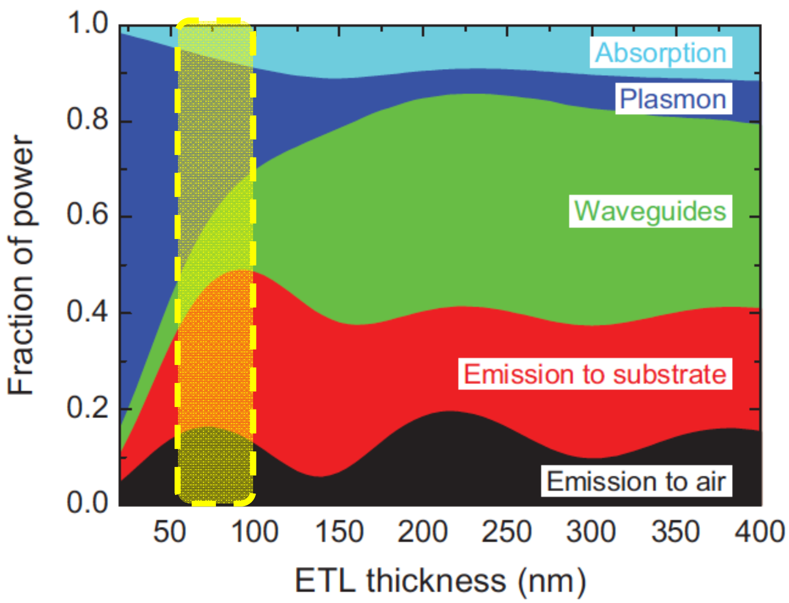
- *n*-doped transport layer to maintain electrical characteristics
- Thicker Bphen:Cs ETL separates EML from top Ag planar electrode
- Far field intensity seems to be stronger at first maxima, but actual outcoupling efficiency is larger at second maxima due to varying dipole power w.r.t. ETL thickness



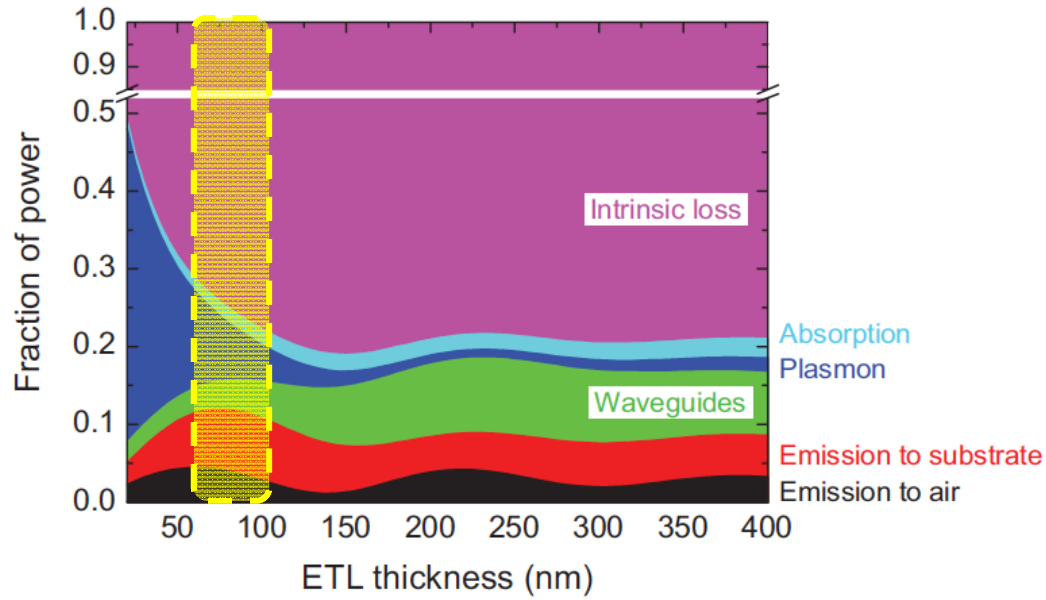


Phys. Rev. B, 85, 115205 (2012)

Loss mechanisms in planar bottom–emitting OLEDs



Amount of power in different modes in Alq_3 OLED, assuming QY = 1

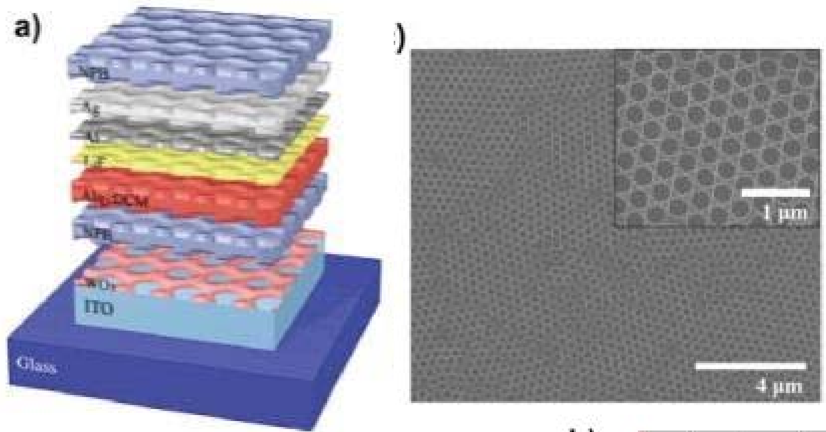


Amount of power in different modes in Alq_3 OLED, assuming QY = 0.2

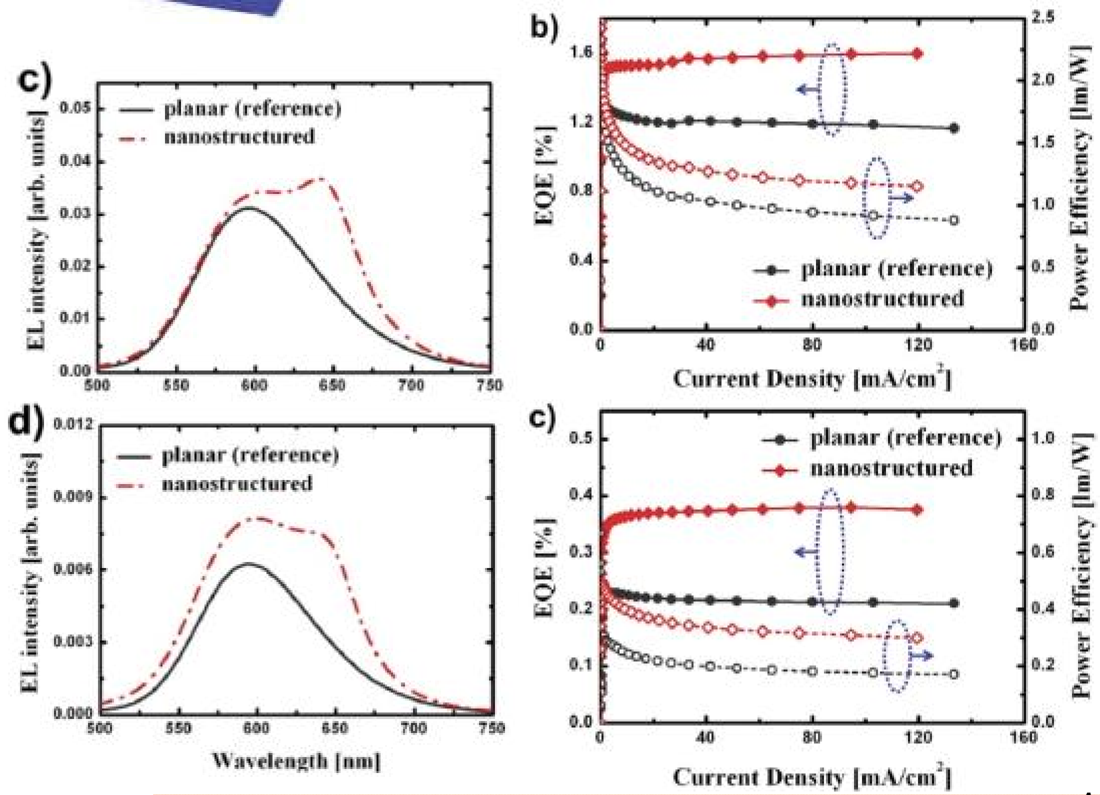
- SPP loss portion heavily varies according to the distance between emitter and metal
- Other factors, like varying QY w.r.t to distance to cathode, also affect SPP portion
- But **within first-order cavity thickness range, SPP loss mode is significant**

W. Brutting et al, *Phys. Status Solidi A* 210, 1, 44 (2013)

SPP mode recovery – periodic perforation



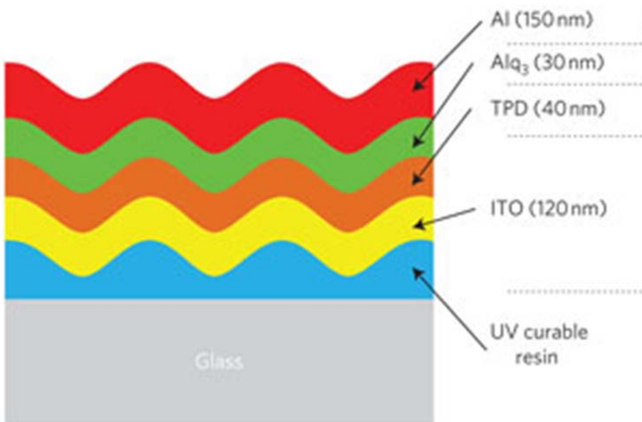
- Perforated WO_3 layer introduces corrugation at top metal electrode
- Applies even for transparent OLEDs
- Highly periodic structure leading to wavelength-dependent enhancement



~30% bottom/~75% top emission enhancement

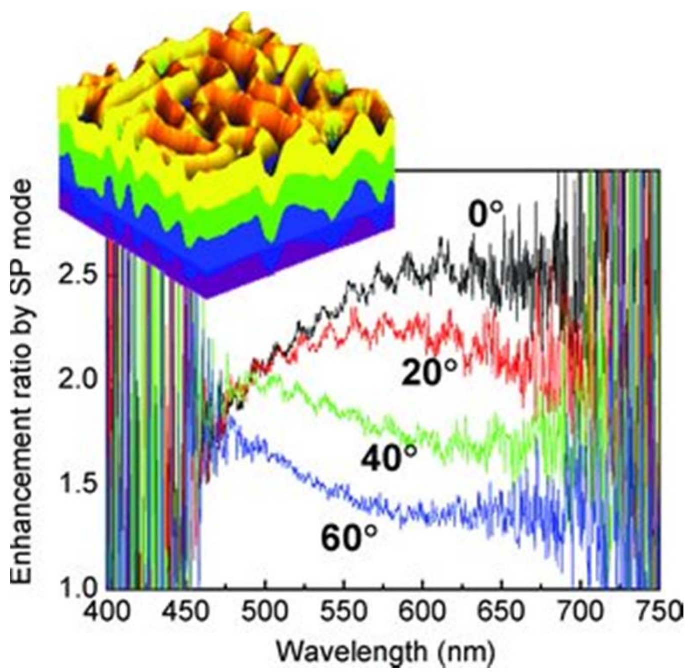
SPP mode recovery – random buckling

[1]

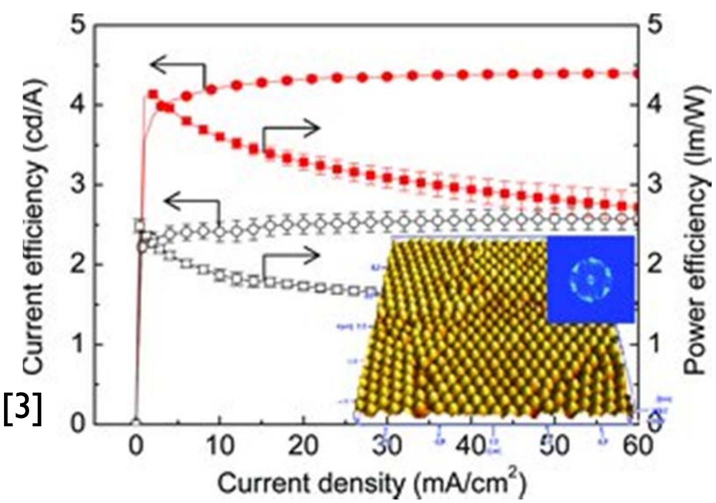


- Random patterns have been successful in dealing with internal waveguided modes as well as SPP modes
- Demonstrated on TPD/Alq_3 or NPB/Alq_3 devices rather than PhOLEDs
- ± angle- and λ-neutral

[2]

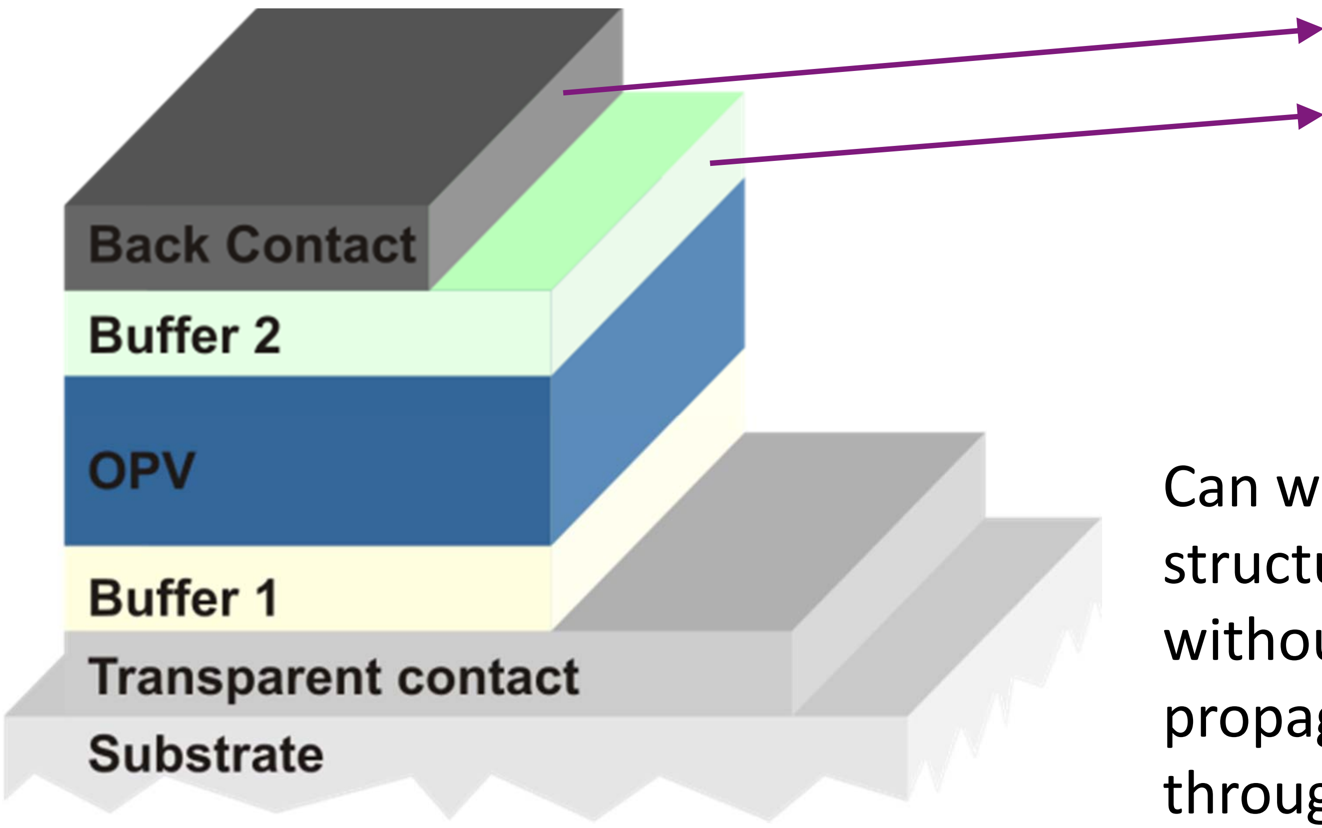


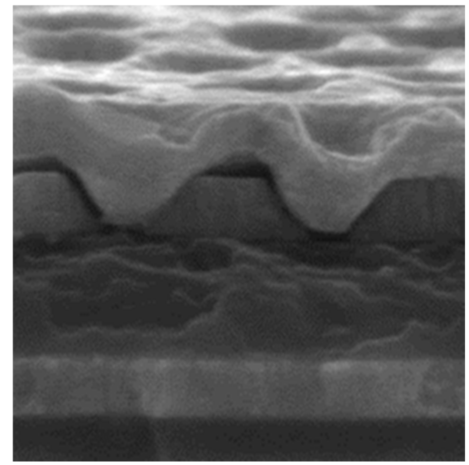
[3]



[1] *Nature Photon.* **4**, 222 (2010)
[2] *Adv. Mater.* **23**, 1003 (2011)
[3] *Adv. Funct. Mater.*, **22**, 3454 (2012)

Optically, OPVs are similar to OLEDs



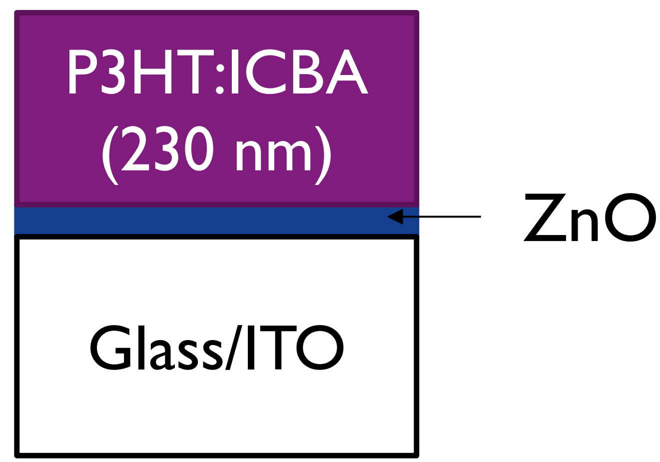


Can we find a way to structure the back contact without requiring to propagate that structure throughout the device?

Solution? Hole-mask colloidal lithography[1]

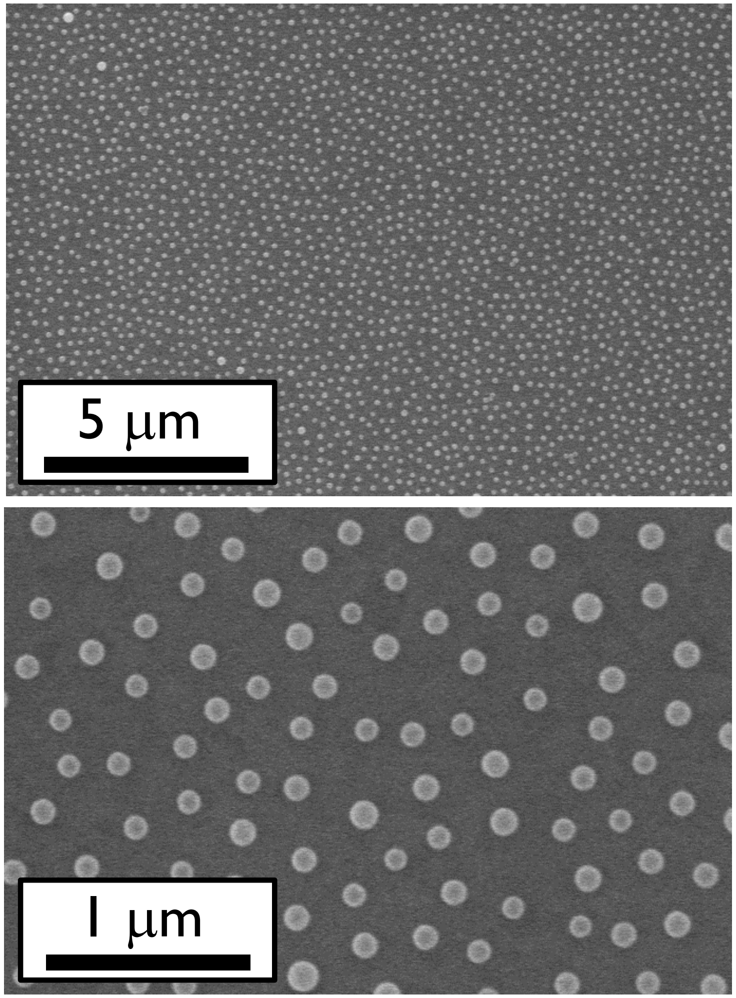
Processing on top of the organic active layer without destroying its electrical and optical properties:

- Use water-based solutions
- At low temperatures

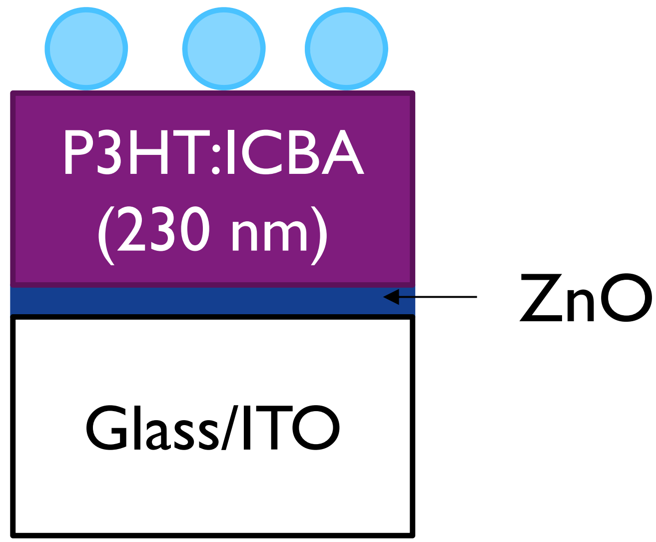


[1] H. Fredriksson et al., *Adv. Mater.* 19, 4297 (2007)

Solution? Hole-mask colloidal lithography[1]



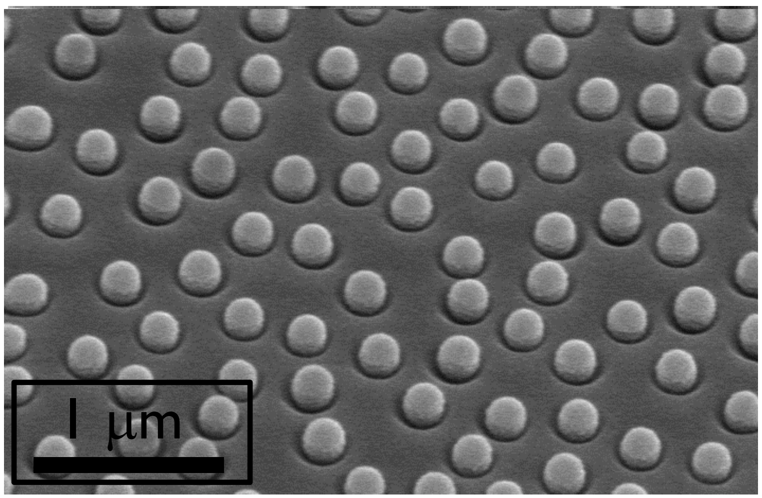
Drop-casting of polystyrene nano-beads (d=140 nm)

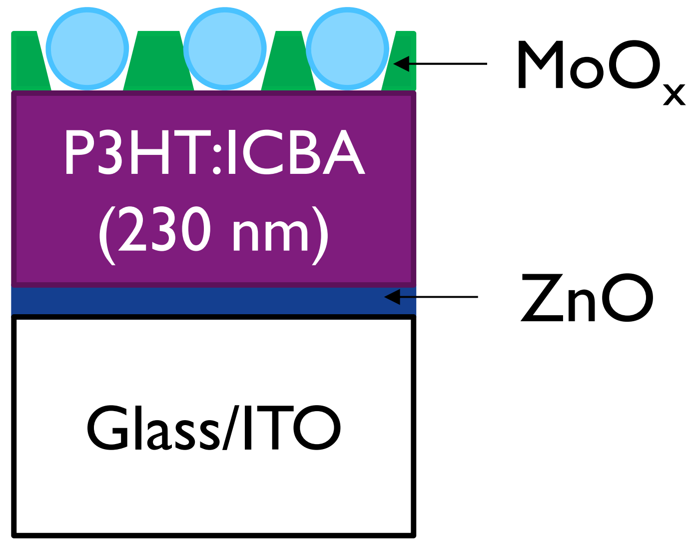


[1] H. Fredriksson et al., *Adv. Mater.* 19, 4297 (2007)

Solution? Hole-mask colloidal lithography[1]

Deposition of MoO_x by thermal evaporation





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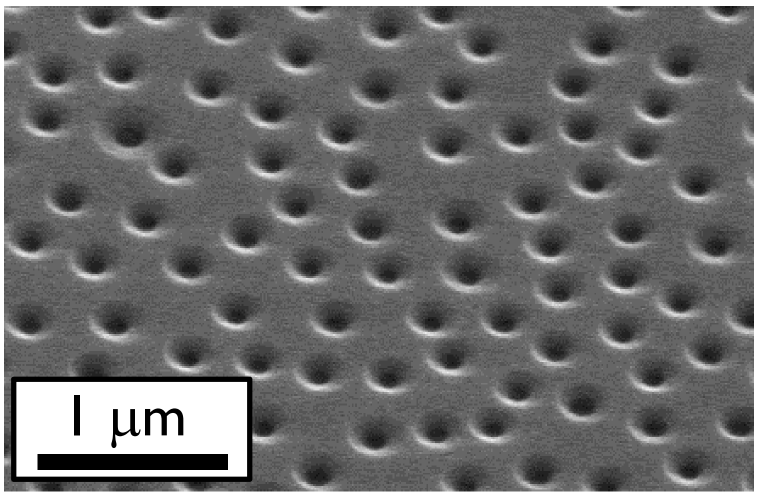
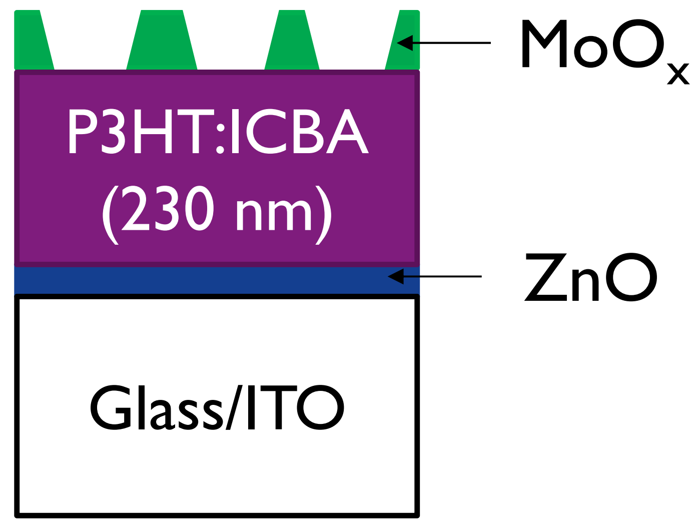
Solution? Hole-mask colloidal lithography[1]

Removal of PS beads

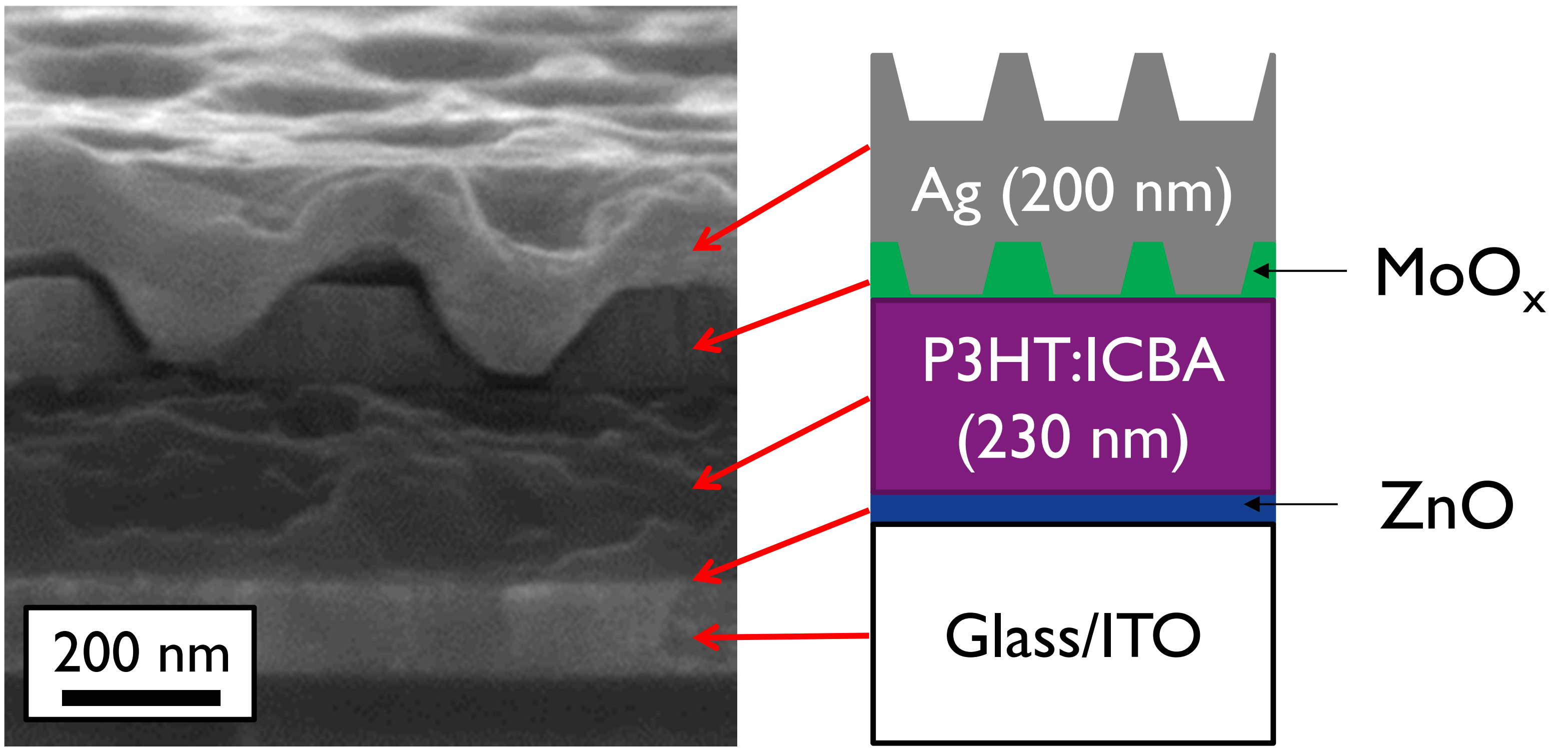




[1] H. Fredriksson et al., *Adv. Mater.* 19, 4297 (2007)

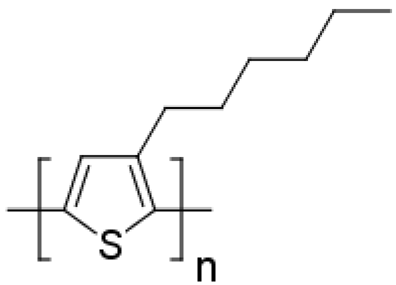
Solution? Hole-mask colloidal lithography[1]

Deposition of MoO_x and Ag by thermal evaporation

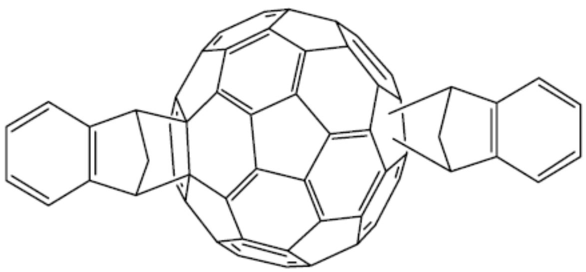


[1] H. Fredriksson et al., *Adv. Mater.* 19, 4297 (2007)

Reference device

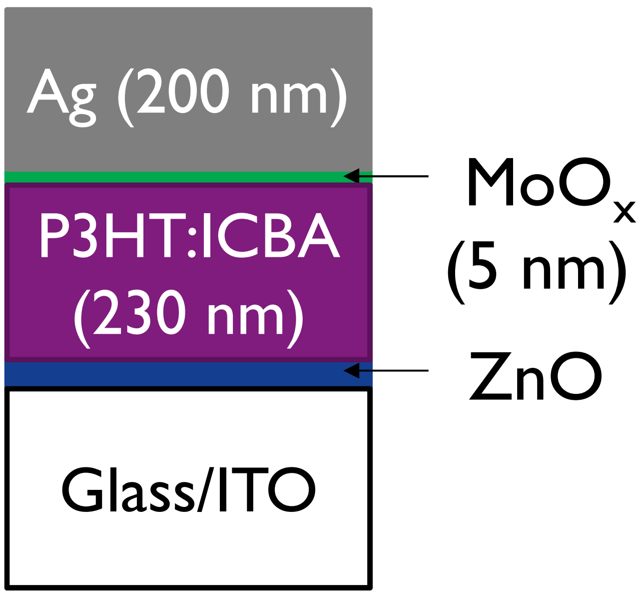


Poly(3-hexylthiophene)
(P3HT)



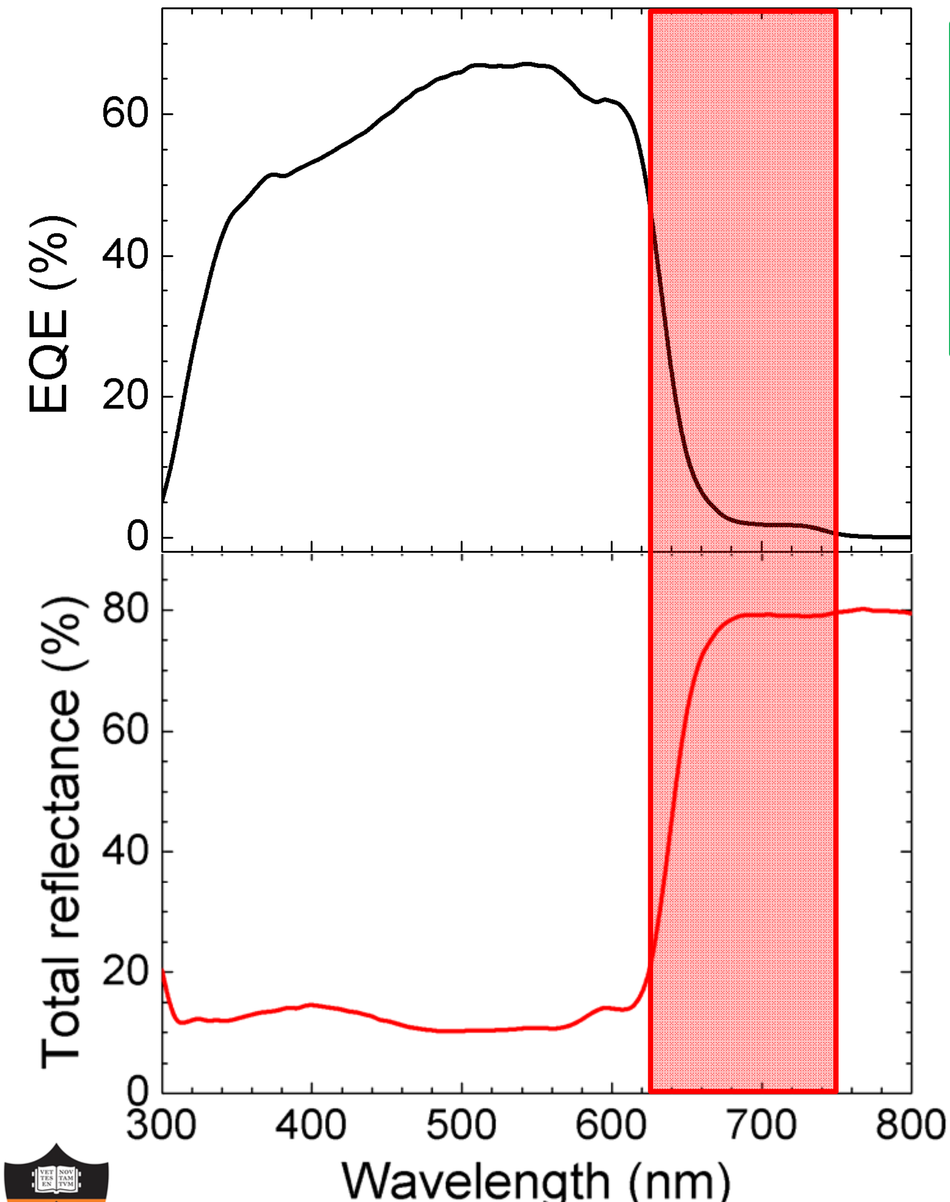
Indene-C_{60} bisadduct
(ICBA)

J_{sc} = 9.86 mA/cm^2
V_{oc} = 780 mV
FF = 68 %
η = 5.26 %

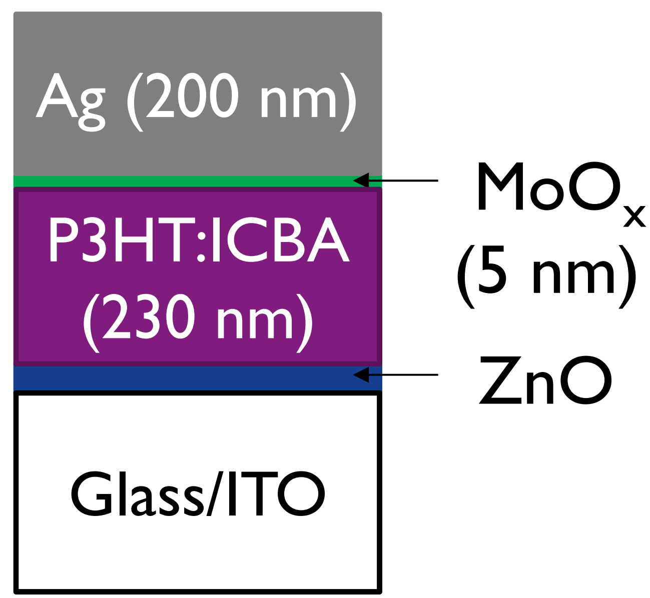


B. Niesen *et al.*, *Adv. Energy Mater.*, *3*, 145 (2013)

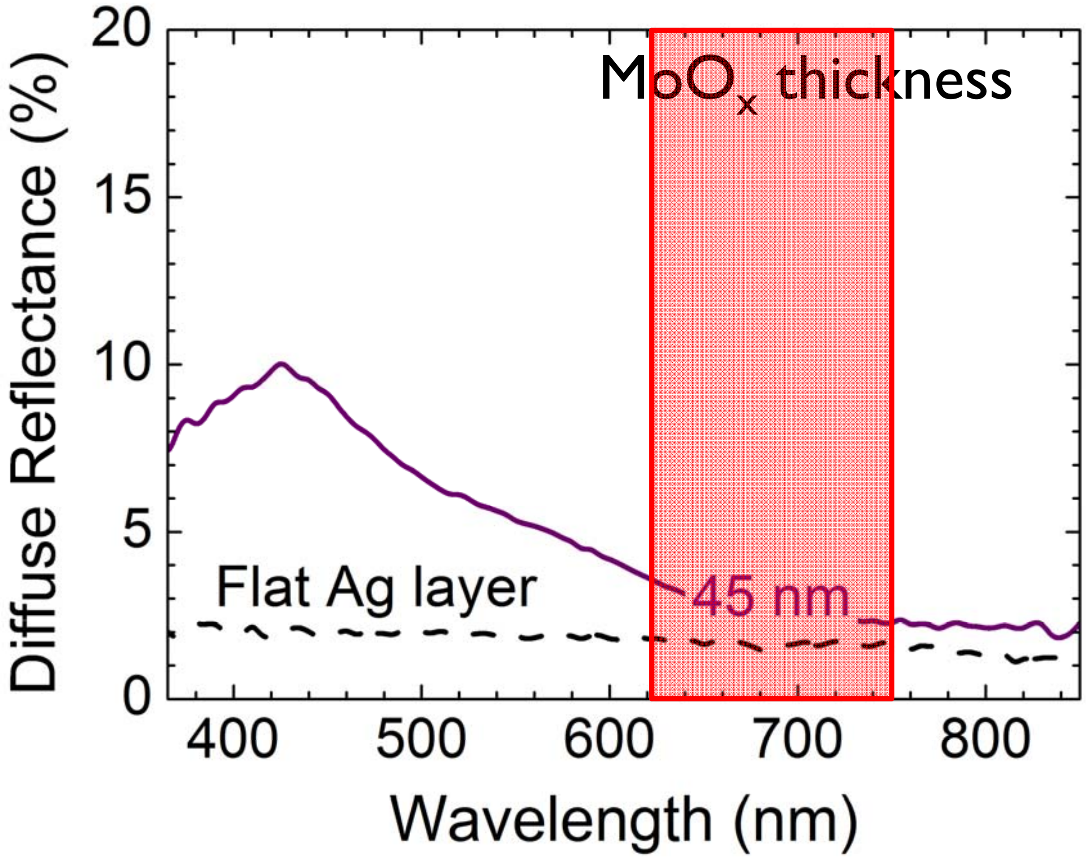
Reference device

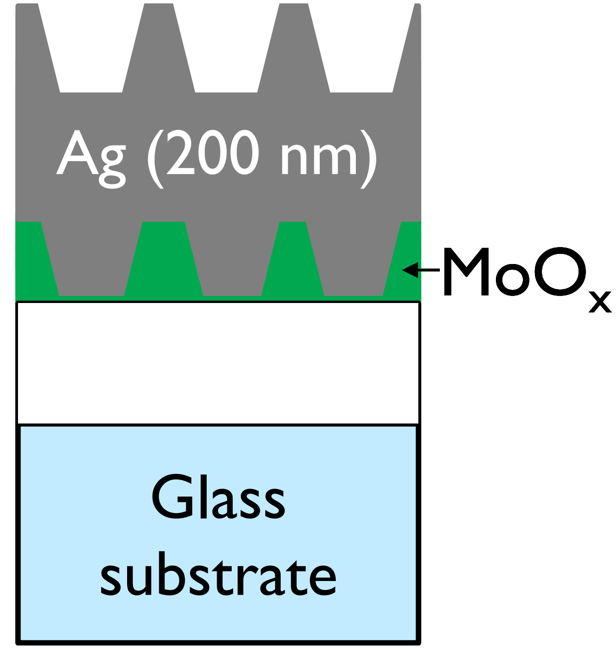


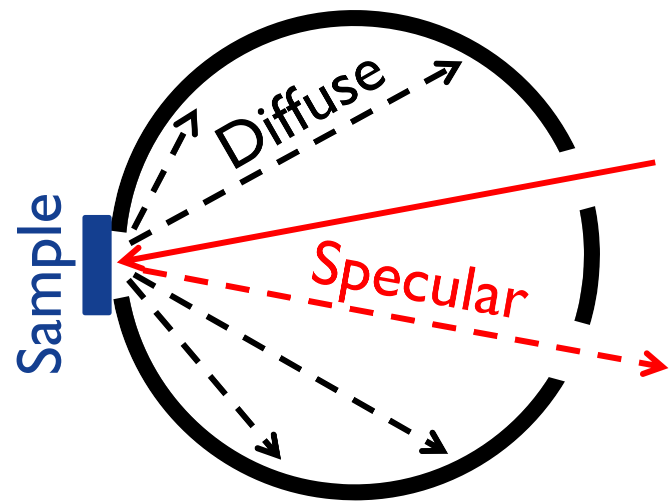
- Saturated absorption at $\lambda < 620$ nm
- Absorption enhancement possible in red absorption tail



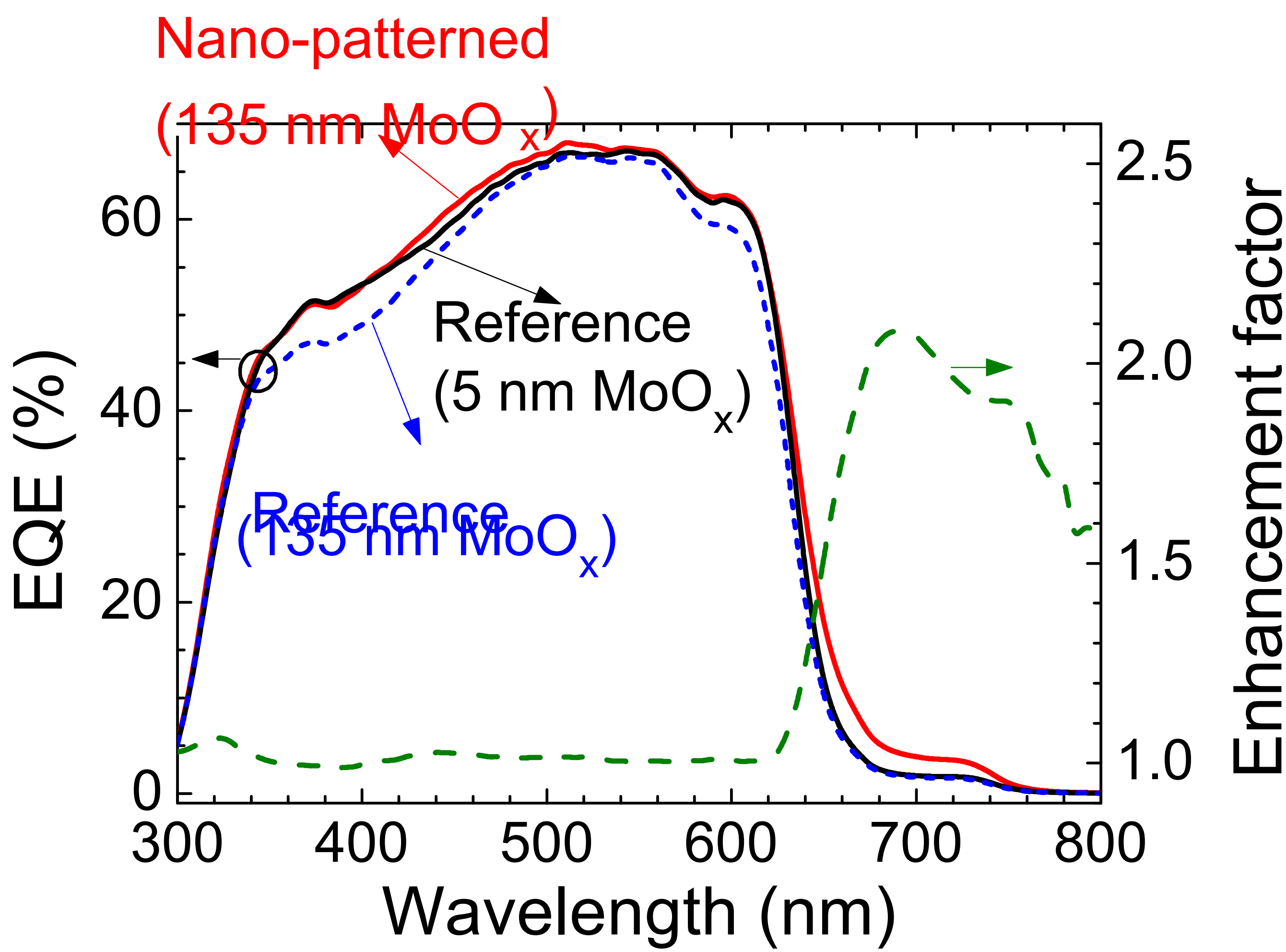
Optical properties of the plasmonic electrode







Plasmonic efficiency enhancement



J_{sc}: 4.4% enhancement, η: 5.28% → 5.56%

B. Niesen *et al.*, *Adv. Energy Mater.*, *3*, 145 (2013)

Conclusions

SPP modes and conventional waveguiding modes co-exist in OLED structures

- Reducing one increases the other in canonical structures
- Distance between metal and emitter critical (near-field effect)

There is a need to find solutions to enable outcoupling of both loss mechanisms

- Potential benefits are tremendous
- Solutions need to ultimately be realizable at low cost and at large scale

Lessons learned from PV field can be helpful, and vice versa

Thank you for your attention!